# Investigating Optimum $SiO_2$ Nanolubrication During Turning of AISI 420 SS

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***Abstract*—AISI 420 martensitic stainless steel is used for making gas and steam turbine blades, steel balls and medical instruments, due to its anti-corrosive properties. Turning of AISI 420 SS would be a worthy procedure specifically in manufacturing high surface finish parts. In this work, effort has been made to investigate the cooling and lubricating performance of $SiO_2$ (silicon dioxide) nanoparticles at different weight concentrations of 0.1g, 0.5g and 1g mixed in a novel developed base fluid (synthetic). The performance of optimum $SiO_2$ based cutting fluid is evaluated based on the turning process with output responses like surface finish and cutting temperature. Taguchi technique was used with standard L9(3**4) orthogonal array. The responses, surface roughness, and cutting temperature were analyzed using S/N (signal-to-noise) and ANOVA (analysis of variance). This analysis identifies the significant input parameter combination to obtain minimum surface roughness and temperature.**

***Keywords-Taguchi; $SiO_2$ nanoparticles; ANOVA; orthogonal array; cutting fluid***

## I. INTRODUCTION

Water was firstly proposed as a cutting fluid to reduce temperature and enhance surface finish and tool life in metal cutting process [1]. Onwards, many cutting fluids were introduced and used by the machining industry. Recently, industries realized the cost, environmental and health issues in the use of these cutting fluids [2-4]. The industry expects a cutting fluid with minimal cost, more output and best quality [5]. Few attempts were made in the past to develop such a cutting fluid by including nanoparticles in it and it was named as nanolubricant, which includes a combination of metallic or non-metallic nanometer sized particle in the cutting fluid. In the past decade more attention was paid to nanolubricants due to their enhanced thermal properties like thermal conductivity and convective heat transfer coefficient [6]. Most commonly used nanoparticles in the base fluid were titanium oxide, molybdenum disulphide and silicon dioxide. Compared to others, $SiO_2$ nanoparticles have shown a significant improvement in machining and thermal properties and a reasonable improvement in lubrication effect [7-11]. These $SiO_2$ nanoparticles impinge between metal surfaces and create rolling action enhancing lubrication [12]. Another study on $SiO_2$ nanolubricant [13] shows 62.67% and 30.86% lower forces in dry machining and application of conventional oil based cutting fluid. Turbine blade materials like AISI 420, do have a high chromium percentage (i.e. 13 to 14%). Turning of these high hardness materials raises high temperature at the cutting zone and more surface roughness on the machined surface. The surface finish of these materials is critical as poor surface finish leads to surface cracks and to fail at high centrifugal forces [14]. There are a few studies in the literature on the machinability of AISI 420 using nanolubricants [8-10] and some of them used DOE (design of experiments) [15]. Frequently used DOE are response surface and Taguchi methods. Response surface method is expensive compared to Taguchi method. Taguchi method suggests a few experiments while keeping the analysis at par with other methods [16].

This work aims to minimize the surface roughness of machined AISI 420 material using $SiO_2$ nanolubricant. The control factors were speed, feed, depth of cut and the weight of $SiO_2$ nanoparticles in the base fluid. The responses considered were surface finish of the workpiece and cutting temperature in the cutting zone. The experiments were planned and conducted using $L_9$ orthogonal array.

## II. MATERIALS AND METHODS

### *A. Workpiece, Tool and Nanoparticles*

The experiments were carried out on a CNC lathe machine (HMT Praga model) as shown in Figure 1. The workpiece material considered for turning was AISI 420 with 50mm diameter and 120mm length.

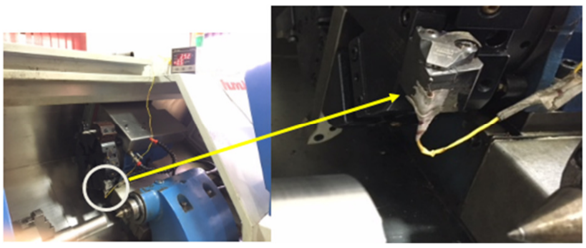

Fig. 1. Cutting temperature measurement with thermocouple.

A HSS (high speed steel) uncoated carbide insert (CNMG 120408) with 0.8mm nose radius was used. The

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workpiece and the cutting tool properties are given in Table I. Each experiment was conducted using a new cutting edge. The size of the $SiO_2$ nanoparticles used in the cutting fluid was 521.4nm (Table II). Adding $SiO_2$ nanoparticles in the cutting fluid may improve the convective heat transfer coefficient and net heat carrying capacity, which is essential requirement for a cutting fluid.

TABLE I. WORKPIECE AND TOOL MATERIAL PROPERTIES

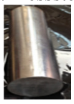
| Material Properties | Workpiece | Cutting tool |
|---|---|---|
| Type | AISI420 martensitic stainlesssteel  | Uncoated HSS carbide insert  |
| Conductivity (W/mK) | 24.9 | 105 |
| Density (kg/m$^3$) | 7800 | 15000 |
| Modulus (GPa) | 200 | 620 |
| Poisson's ratio | 0.28 | 0.22 |
| Specific heat $C_p$ (J/kg$^o$C) | 460 | 670 |

TABLE II. $SiO_2$ NANOPARTICLE PROPERTIES

| Properties | $SiO_2$ Nanoparticles |
|---|---|
| Physical structure | Amorphous crystalline powder |
| Conductivity (W/cm K) | 0.015 |
| Density (g/cm3) | 2.1 |

## *B. Plan of Experiments*

All the experimental procedures used Taguchi $L_9$ orthogonal array. Considered control parameters were speed, feed, depth of cut and $SiO_2$ nanoparticle concentration in the base fluid. All parameters were kept at 3 levels: low, medium and high. The responses measured were surface roughness and temperature at the cutting zone. Each experiment was repeated thrice to ensure repeatability and the average value of these three experiments is given below. The list of planned experiments is specified in Table III.

TABLE III. DESIGN OF EXPERIMENTS AND CONTROL FACTORS

| # | Orthogonal array L9 (3**4) | | | | Speed-A (m/min) *Vc* | Feed-B (mm/rev) *f* | Depth of Cut-C (mm) *ap* | $SiO_2$ *-D (g) |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | | | | |
| 1 | 1 | 1 | 1 | 1 | 150 | 0.10 | 0.10 | 0.1 |
| 2 | 1 | 2 | 2 | 2 | 150 | 0.15 | 0.20 | 0.5 |
| 3 | 1 | 3 | 3 | 3 | 150 | 0.20 | 0.30 | 1 |
| 4 | 2 | 1 | 2 | 3 | 175 | 0.10 | 0.20 | 1 |
| 5 | 2 | 2 | 3 | 1 | 175 | 0.15 | 0.30 | 0.1 |
| 6 | 2 | 3 | 1 | 2 | 175 | 0.20 | 0.10 | 0.5 |
| 7 | 3 | 1 | 3 | 2 | 200 | 0.10 | 0.30 | 0.5 |
| 8 | 3 | 2 | 1 | 3 | 200 | 0.15 | 0.10 | 1 |
| 9 | 3 | 3 | 2 | 1 | 200 | 0.20 | 0.20 | 0.1 |

* concentration

## III. RESULTS AND DISCUSSION

The responses obtained were analyzed with S/N ratio and significant factors were also identified. The smaller-the-better S/N ratio equation was chosen for the responses surface roughness and cutting temperature:

$$Signal\ to\ Noise\ Ratio = -10\,log[\frac{1}{n}\sum_{i=1}^{n}(y_i^2)] \quad (1)$$

The responses and corresponding S/N ratios are given in IV. ANOVA was done to find significant parameters and the optimal concentration of $SiO_2$ nanoparticle in the based fluid to get least surface roughness and cutting temperature.

TABLE IV. EXPERIMENTAL AND S/N RESULTS

| # | *Vc* | *f* | *ap* | $SiO_2$ (g) | Surface Roughness | | Cutting Temperature | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Ra (µm) | Ra. S/N (dB) | T (°C) | T. S/N (dB) |
| 1 | 150 | 0.10 | 0.1 | 0.1 | 0.47 | 6.55 | 169 | -44.5 |
| 2 | 150 | 0.15 | 0.2 | 0.5 | 0.35 | 9.11 | 162 | -44.1 |
| 3 | 150 | 0.20 | 0.3 | 1 | 0.26 | 11.7 | 148 | -43.4 |
| 4 | 175 | 0.10 | 0.2 | 1 | 0.49 | 6.19 | 153 | -43.6 |
| 5 | 175 | 0.15 | 0.3 | 0.1 | 0.64 | 3.87 | 178 | -45.0 |
| 6 | 175 | 0.20 | 0.1 | 0.5 | 0.53 | 5.51 | 167 | -44.4 |
| 7 | 200 | 0.10 | 0.3 | 0.5 | 0.58 | 4.73 | 173 | -44.7 |
| 8 | 200 | 0.15 | 0.1 | 1 | 0.29 | 10.7 | 164 | -44.2 |
| 9 | 200 | 0.20 | 0.2 | 0.1 | 0.61 | 4.29 | 182 | -45.2 |

A 5% level of significance was considered for ANOVA. The ANOVA results for surface roughness, cutting temperature are discussed in the following sections.

### *A. Surface Roughness*

The S/N ratios of surface roughness varied from 3.87dB to 11.7dB. Optimal combination of factors for minimum surface roughness can be obtained from the plot in Figure 2. This shows that 150m/min cutting speed, feed 0.15mm/rev, 0.1mm depth of cut and 1g $SiO_2$ nanoparticle combination gives minimum surface roughness. Among all 4 factors the concentration of $SiO_2$ nanoparticles was having an S/N ratio of 9.55dB. This emphasizes the importance of $SiO_2$ nanoparticles in controlling the surface roughness of the parts produced. Detailed S/N ratios of all input parameters for different levels are presented in Table V.

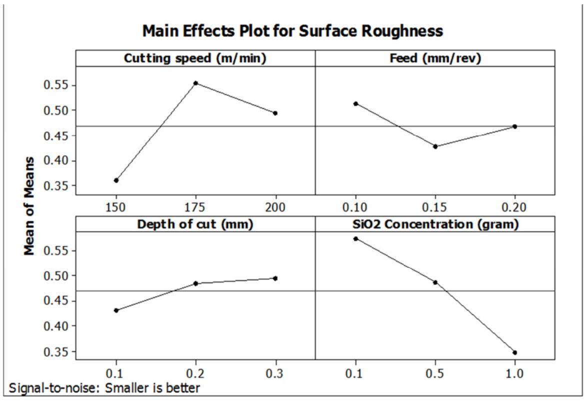



Fig. 2. Optimum combination of control factors for minimum surface roughness (µm).

ANOVA for surface roughness was analyzed and the results are given in Table VI. These results show 50.65% contribution from concentration of $SiO_2$ nanoparticles showing its significance. Regarding the other factors, speed is contributing 37.66%, feed 7.14% and depth of cut 4.55% in reducing surface roughness. The interaction plot for the control factors is shown in Figure 3. In general, the parallel lines in the interaction plot show no interactions and the intersecting lines represent the presence of interactions between control factors. Figure 3 shows that most of the factors were having a two way interaction in influencing the output surface roughness.

TABLE V. RATIO OF S/N RESPONSE FOR SURFACE ROUGHNESS

| Level | Cutting Speed | Feed | Depth of cut | $SiO_2$ concentration |
|---|---|---|---|---|
| 1 | 9.12 | 5.82 | 7.60 | 4.90 |
| 2 | 5.19 | 7.91 | 6.53 | 6.45 |
| 3 | 6.59 | 7.16 | 6.76 | 9.55 |
| Δ | 3.93 | 2.08 | 1.07 | 4.64 |
| **Rank** | **2** | **3** | **4** | **1** |

TABLE VI. ANOVA FOR SURFACE ROUGHNESS

| Sources | Degrees of freedom | Sum of squares | Mean of squares | Contribution percentage (%) |
|---|---|---|---|---|
| Cutting speed | 2 | 0.058 | 0.029 | 37.66 |
| Feed | 2 | 0.011 | 0.005 | 7.14 |
| Depth of cut | 2 | 0.007 | 0.003 | 4.55 |
| $SiO_2$ nanoparticle concentration | 2 | 0.078 | 0.039 | 50.65 |
| Error | 0 | | | |
| **Total** | **8** | **0.154** | | **100** |

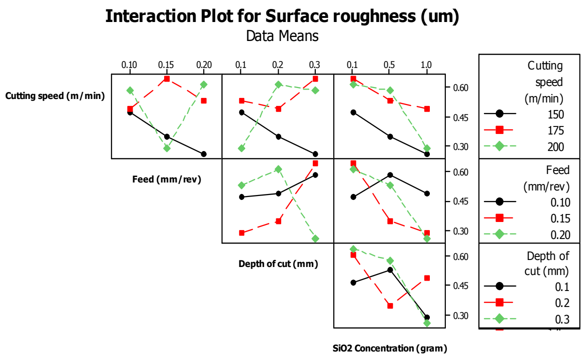



Fig. 3. Control factors interaction for surface roughness (μm).

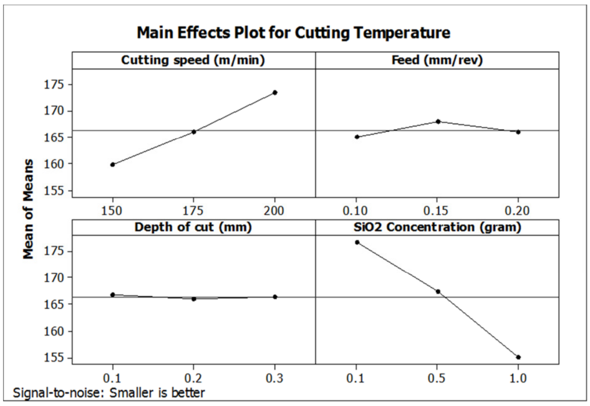



Fig. 4. Optimum combination of control factors for lower cutting temperature (°C).

## *B. Cutting Temperature*

A similar study was carried out considering cutting temperature. Optimal parameter combination for minimal temperature may be interpreted from Figure 4. The S/N ratio for cutting temperature ranged from -45.2dB to -43.3dB and is given in Table IV. The S/N ratio response table at different levels of input parameters is given in Table VII. The optimal parameter combination was chosen based on the S/N ratio value at the particular level. The optimal parameter condition for minimum cutting temperature is 150m/min speed (-44.05dB), 0.1mm/rev feed (-44.34dB), 0.2mm depth of cut (-44.38dB) and 1gram (-43.80 dB) $SiO_2$ nanoparticle concentration. As before, for the cutting temperature the nanoparticle concentration is having the highest S/N ratio, proving its significance among other factors. The ranking of the parameters obtained by the value of S/N ratio was specified in Table VII. The ANOVA results for the cutting temperature are given in Table VIII. The results show that concentration of $SiO_2$ nanoparticle contributed 70.53% in the temperature variance. Among the other factors, cutting speed contributes 27.97% and the contribution from depth of cut and feed are negligible.

TABLE VII. S/N RESPONSE FOR CUTTING TEMPERATURE

| Level | Cutting Speed | Feed | Depth of cut | $SiO_2$ concentration |
|---|---|---|---|---|
| 1 | -44.05 | -44.34 | -44.44 | -44.94 |
| 2 | -44.39 | -44.50 | -44.38 | -44.47 |
| 3 | -44.77 | -44.37 | -44.39 | -43.80 |
| Δ | 0.72 | 0.16 | 0.06 | 1.14 |
| **Rank** | **2** | **3** | **4** | **1** |

TABLE VIII. ANOVA FOR CUTTING TEMPERATURE

| Sources | Degrees of freedom | Sum of squares | Mean of squares | Contribution percentage (%) |
|---|---|---|---|---|
| Cutting speed | 2 | 281 | 140 | 27.97 |
| Feed | 2 | 14 | 7 | 1.40 |
| Depth of cut | 2 | 1 | 0 | 0.10 |
| $SiO_2$ nanoparticle concentration | 2 | 708.7 | 354.3 | 70.53 |
| Error | 0 | | | |
| **Total** | **8** | **1004.7** | | **100** |

Interaction effect for the factors is shown in Figure 5. In this, most of the lines representing the factors are non-parallel showing the two way interactions. In Figure 5, irrespective of other factors, the temperature at the 1-gram concentration of $SiO_2$ nanoparticle is lower. This can be attributed to the increased heat carrying capacity and thermal conductivity of nanoparticles in the base fluid. The general regression equations were obtained based on the experimental results and are given below:

$$T(^{o}C) = 130 + 0.273 \times V_c + 10.0 \times f - 1.67 \times ap - 24.1 \times X \quad (2)$$

$$Ra(\mu m) = 0.144 + 0.00267 \times V_c - 0.467 f + 0.317 \times ap - 0.253 \times X \quad (3)$$

where $V_C$ is speed used, *f* is feed, depth of cut is *ap* and the concentration of $SiO_2$ nanoparticles is *X*. The R-square values obtained for cutting temperature and surface roughness are 98% and 73.3% respectively. The given regression polynomial equations are useful for predicting the cutting temperature and surface roughness.

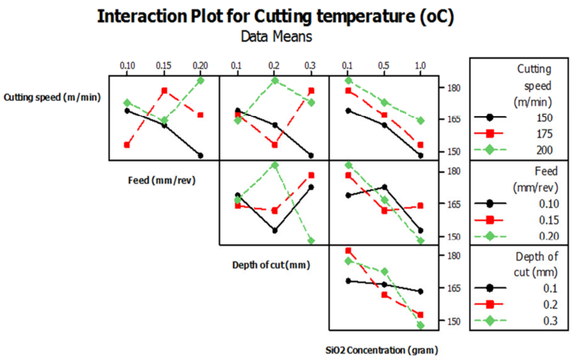



Fig. 5. Control factors interaction for cutting temperature (°C).

## IV. CONCLUSIONS

In the present work, an optimal level of $SiO_2$ nanoparticles concentration in a base fluid for minimal cutting temperature and surface roughness was determined. The machining experiments were conducted on AISI 420. Speed, feed, depth of cut and $SiO_2$ nanoparticle concentration were considered as factors and Taguchi $L_9$ orthogonal array was used to design the experiments. Based on the responses measured from the experiments the following observations were made:

- Minimum surface roughness was observed on the machined surface of the workpiece for 1g of $SiO_2$ nanoparticles in base fluid, 150m/min cutting speed, 0.15mm/rev feed and 0.1mm depth of cut.
- Minimum cutting temperature was observed for 1g of $SiO_2$ nanoparticles in base fluid, 150m/min cutting speed, 0.10mm/rev feed and 0.2mm depth of cut.
- Based on ANOVA it was observed that $SiO_2$ nanoparticles contribute 50.65% in reducing surface roughness and 70.53% in obtaining minimum cutting temperature.
- A polynomial equation was proposed to obtain a relationship between input parameters and responses, i.e. cutting temperature and surface roughness.

From these results, it can be concluded that the machining performance, in terms of cutting temperature and surface finish of workpiece, was improved by adding 1g $SiO_2$ nanoparticles in the base fluid. These results give a direction to develop new cutting fluid with $SiO_2$ nanoparticles.

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